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AN OVERVIEW OF ADDITIVE MANUFACTURING – APPROACHES, TECHNIQUES, TRENDS AND CHALLENGES IN MANUFACTURING SCENARIO

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ABSTRACT

Nowadays, Additive Manufacturing (AM) otherwise called 3D (Three Dimensional) Printing is a prominent one in the emerging industrial scenario. The domain called Additive Manufacturing (AM) is an emerging technology for multifaceted applications, developing novel materials and exhibiting excellent mechanical, physical and chemical properties of the end product. The Additive Manufacturing technique of bottom-up approach which is beneficial than Conventional Methods of top-down approach in all aspects except certain limitations like Production time; Product Size; Setup Cost; Statutory Regulations. Irrespective of the challenges, there is a scope for commercializing AM products in the global market, which in turn leads to the production savings of less than 50% and an increased production speed of more than 400 % when compared to conventional methods of optimizing the constraints. The aim of the paper is to overview of Additive Manufacturing on modeling approaches, techniques, trends and its challenges in the application of AM to attain its full potential.

KEYWORDS: 3D Printing, Additive Manufacturing & Bottom Up Approach

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Original Article

INTRODUCTION

Additive Manufacturing (AM) is an approach for producing an extensive range of Lattice structures with intricate geometries from 3D model data. The outcome of this results in the development of exceptionally light and stable products. AM has been broadly applied in various industrial fields, including Aerospace, Biomechanical, Construction, Defence and Medical applications. The practice of Additive Manufacturing has reduced the additional expenditures that are experienced in the process of Product Development. It has been predicted that in 2020, around 50% of 3D printed commercial Products will globally revolve around the industrial sector. Nevertheless, the evolution of AM in recent years is being remarkable, the government / educational societies support in the form of an increased grant, research, and development leads for the fast changeover from conventional methods to 3D printing technologies shortly (Ngo, Kashani, Imbalzano, Nguyen, & Hui, 2018). 3D printing with sand, plastic and other particles has found feasibility in the industrial applications (Nickels, 2016). It is innately beneficial than conventional subtractive techniques of manufacturing and embraces the possibility to decouple economic and social importance establishment from the environmental influence of business happenings; Benefits of this technology are extended product life, improved resource efficiency, and Reconfigured Value Chains. In spite of these potential benefits, AM has not been adequately explored from a sustainability view (Ford & Despeisse, 2016). In this

technique, there are possibilities to use different materials like metals, ceramics, composites, Polymers, biomaterials, etc., those are processed through various printing techniques like Stereolithography (SLA), Fused Deposition Modelling (FDM), Laminated Object Manufacturing (LOM), Selective Laser Melting (SLM), Selective Laser Sintering (SLS), Inkjet Printing (IP), Directed Energy Deposition (DED),3D Gel Printing(3DGP) for different applications with challenges. There is always complexity in geometry available in every additive technique inherently. AM additionally presents the possibility to produce complex, materials with different composition, properties, and microstructure that are difficult through traditional methods (Jared et al., 2017). These technologies claim high standards, not only in Material Selection, finishing quality and but also about measurable sides such as increased productivity. Nowadays, the AM objective was to develop rapid processes that are even more affordable and reduce the limitations (Bechmann, 2014). Growths in Additive Manufacturing are appealing about possibilities in novel design, parts, and production standards. Whereas abundant effort is needed to bring Design for AM to maturity, businesses, both small and large scale, are exploring and espousing AM for end-use products at an astonishing level (Kathryn et al., 2016). 3D printing is not to say the lowest-cost choice. In detail, for many domains, it is often excessively costly. However, the flexibility existing in 3D printing is the complexity of free, its strength prevails in its adaptability (Winkless, 2015). The technology enables the firms to produce an entirely new product that was impossible to make through conventional way and exposing new chances for manufacturing and supply chain globally. It makes existing products better as well as enabling firms to manufacture entirely new ones that were previously impossible to form (Attaran, 2017). The Capabilities of Additive Manufacturing than Conventional Manufacturing as follows:

- Flexibility in Design like curved shapes; it enables the creation of any complex geometry due to layer-wise fabrication approach.
- Less Geometric Complexity Cost, there is no extra cost incurred due to the additional tool, fabrication time, and increased operating expenses.
- Single Part Assembly with relative motion capabilities is possible.
- Time and cost efficiency in productivity, lower inventory cost and reduces the cost associated with supply chain and delivery.
- Ability to conduct complicated manufacturing process and the possibility of customized fabrication (Lu, Li, & Tian, 2015).
- Additive Manufacturing (AM) can fabricate any complicated geometry part in any location at any quantity using any material for any industrial application (Lu et al., 2015).
- Potential to produce Functional Graded Materials (FGM) with high accuracy and controllability with tailored properties, especially in aerospace and biomedical (Klocke et al., 2017) (Naebe & Shirvanimoghaddam, 2016). Downloading a 3-D printing file of small spare parts and users can produce the parts on their own, will become micro-manufacturers (Attaran, 2017).

Finally, Additive Manufacturing will become a boon for manufacturing industries as equivalent to subtractive manufacturing processes (Lu et al., 2015). There are dual vital encounters in developing the next-generation of AM processes: (i) Enhancement in speed, Accuracy, and resolution with lower consumption of energy. (ii) Development of

novel materials by AM with suitable physical, chemical and mechanical properties (Lee, An, & Chua, 2017). There is a future prediction statement; the majority of private consumers will have AM printers at home itself. The objective of this paper is to deliver an overview of Additive Manufacturing (AM) on modeling approaches, techniques, trends and its challenges in the application of AM. This review will help the researchers, students, engineers, and industrialists to acquire the knowledge and apply these concepts in their extensive work.

OVERVIEW OF ADDITIVE MANUFACTURING

The process initiates with a 3D solid model as a digital CAD file and then sliced into several numbers of layers by available software. Each layer is created by appropriate Additive Manufacturing techniques to form a printed primitive (Ho, Ng, & Yoon, 2015). Figure 1 shows the process of 3D printing as follows.

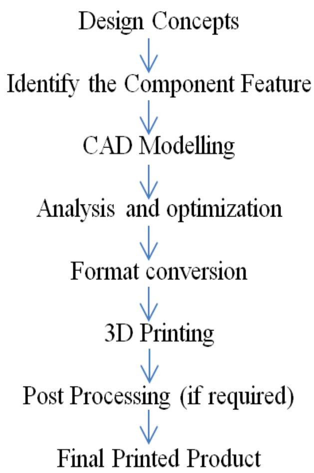


Figure 1: Flow Diagram for 3D Printing Process (Ho et al., 2015)

MODELLING APPROACH IN ADDITIVE MANUFACTURING

The Models are used to predict the process performance. Each model is mentioned in Figure 2. For different models, various Analysis and Simulation methods are followed like Monte Carlo (MC) Simulation, Discrete Element Method, Computational Fluid Dynamics (CFD), and Finite Element Method. There are relations between different models and the ambiguity in the model of powder bed will propagate to the uncertainty in the model of solidification, which will then be presented in the model of residual stress (Hu & Mahadevan, 2016). By using modules of fluid flow and heat transfer in COMSOL Multiphysics, process modeling on a macro scale is accounted (Rolchigo et al., 2017). The MC can predict 3D microstructures with hundreds of heat source passes with low computational costs (Rodgers, Madison, & Tikare, 2017). By Open FOAM computational fluid dynamics (CFD) cellular automata-finite element (CAFE) approach, the distribution of powder size, melt flow, grain structure evolution and precipitation are studied (Panwisawas et al., 2017). The Finite element approaches for modelling heat transfer analyses of metal deposition are investigated, unusually both inactive and quiet element activation are reviewed. A novel hybrid quiet idle metal deposition method is also suggested to provide better results with faster computation time (Michaleris, 2014). The processing and microstructure interrelationship is accounted by Three Dimensional Cellular Automata Fluid Dynamics (3D CAFD) (Zinovieva, Zinoviev, & Ploshikhin, 2018). The software for Finite-Element Analysis (FEA) like ABAQUS and Diablo are the tools for performance modeling. These software represents the response of physical mechanisms for various loading conditions (boundary conditions) using governing equations and also calculate the internal stress in a part and failure modes (Francois et al., 2017).

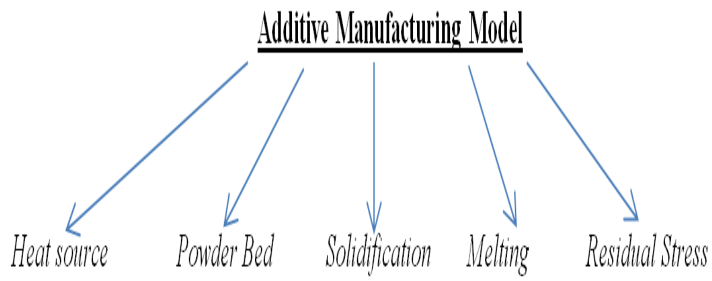


Figure 2: Models on Additive Manufacturing

ADDITIVE MANUFACTURING (AM) TECHNIQUES

Additive Manufacturing (AM) Techniques has been well-known for producing complex geometry with better resolutions and accuracy to meet the demands. AM techniques show the ability to build large and complex structures, reducing the defects in the lattice structure and improving mechanical properties are some of the driving factors in industrial scenario. These Techniques are mostly used for modeling, prototyping, and producing Net Shape Components (Khan, Mateus, Lorger, & Mitchell, 2017).

The Table.1 illustrates the summary of various techniques in Additive Manufacturing. The Beneficial AM Techniques in Aerospace field are SLM and SLS for Lightweight structures, Fuel Reduction, Rapid Tooling, Fixturing and FDM, 3DP preferred for Interior Customisation. The adopted AM Techniques in the Automotive sector are FDM and 3DP for customization, SLM and SLS are beneficial in producing Lightweight Structure. For smart microsystems and miniaturization in Electronic Domain, Micro SLS and SLA are followed. In Medical field, for Biomedical Manufacture SLS, SLA and FDM are favored whereas, for minimally invasive surgery, SLM is preferred (Pinkerton, 2016).

Table 1: Summary of AM Techniques

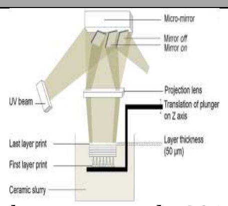
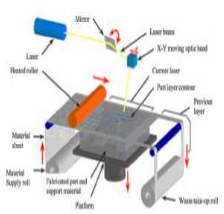
Technique	Schematic	Characteristics	Materials	Applications	Remarks
SLA	 (Dehurtevent et al., 2017)	High-quality parts < 10 µm fine resolution	Polymer, Nano Composites	Prototyping especially in Biomedical Implants	Photopolymer is required
FDM	 (Bikas et al., 2016)	Cost is Low, High Speed and Simplicity and Design	Thermoplastics Polymer, Fibre Reinforced Composites	Manufacturing of Advanced Composites, Rapid Prototyping	Poor surface quality and Layer by Layer appearance
LOM	 (Ahn et al., 2012)	Reduction in cost incurred in tooling and manufacturing time is low, complex structures are not recommended	Paper, Ceramics, Composites	Smart Structures, Paper Manufacturing, Foundry Industries	Post Processing is required to enhance the surface quality

Table 1:Contd.,

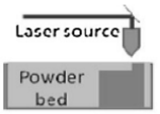
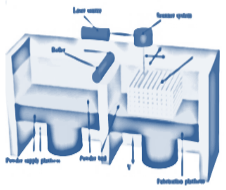
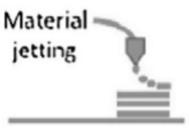
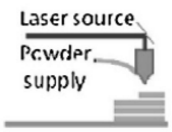
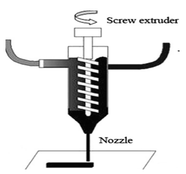
SLM	 (Bikas et al., 2016)	Anisotropic microstructural and Residual Stress effects	Metal (Aluminium and Steel), Polymers, Ti-6Al-V, CP- Ti ceramics (in Powder form)	Bioengineering, Aerospace, and Electronics, Medicines	Post Processing is required
SLS	 (Ngo et al., 2018)	Powders are fused at the molecular level	Metal, Ceramics, Alloy Powder, Thermoplastics (require binding material)	Bioengineering, Aerospace, and Electronics, Medicines	Post Processing is required
IP	 (Bikas et al., 2016)	Efficient and Fast, Flexibility in Design, Printing Complex Structures	Ceramics	Scaffolds for Tissue Engineering	Wax-based inks, Liquid Suspensions method is followed
DED	 (Bikas et al., 2016)	Controlled Microstructure with Exceptional Mechanical Properties, and Accurate Composition Control	Metals (Powder Form), Polymers and Ceramics (Wire form)	Repair technologies in aerospace sectors, Biomedical implants	Preferable for Repairing activities instead of remanufacturing of special components
3DGP	 (Ren et al., 2016)	Printing Efficiency is High, and Fast Flow-ability	Stainless Steel, Thermoplastic, Ceramics, Composites (Complicated Nozzle Design)	Gear Manufacturing	The catalyst is used for acceleration of the process

Table 1 : Summary of AM Techniques (Ngo et al., 2018) (Ho et al., 2015) (Gao et al., 2015)(Ren, Shao, Lin, & Zheng, 2016)(Srinivas & Babu, 2017)(Olakanmi, Cochrane, & Dalgarno, 2015)(Derby, 2015)(Bikas, Stavropoulos, & Chryssolouris, 2016)(Dehurtevent et al., 2017)(Ahn, Kweon, Choi, & Lee, 2012)(Fina, Goyanes, Gaisford, & Basit, 2017)(Herzog, Seyda, Wycisk, & Emmelmann, 2016)

LATEST TRENDS IN THE APPLICATION OF AM

In Medicine Manufacturing, Several kinds of Drug Delivery Systems (DDS) have been established using 3D Printing with variations of drugs and active agents (Deng Guang Yu, Li-Min Zhu, Christopher J. Branford-White, 2008). SLS 3D Printing is used to produce oral medication loaded products without degradation using pharmaceutical grade excipients, i. e., medicine manufacturing, See Figure 3 (Fina et al., 2017). Solid Free Form (SFF) techniques are used to produce freeform geometries offer a unique alternative for producing DDS with complex in shape and microstructure (Jonathan & Karim, 2016).

Figure 3: Printed Formulation Yellow in Colour (Fina et al., 2017)

In Engineering domain, Fabrication to Micro and Nanoscales (Lu et al., 2015) (Example: Polymer Nanoparticle composites to exhibit excellent properties like tensile strength and impact resistance (Bernardo, Amaro, Pinto, & Lopes, 2016)) and ability to create parts embedded with lattice structure are highlighted in Figure 4 (Maskery et al., 2014).

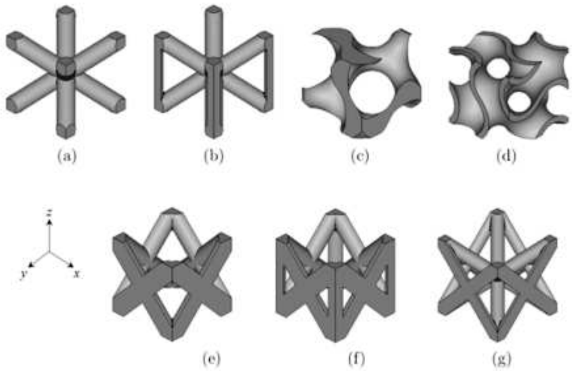


Figure 4: Lattice Structure: (a) BCC (b) BCCz (c) Gyroid (d) Matrix Phase of D-Gyroid (e) FCC (f) PFCC (g) F2BCC (Maskery et al., 2014)

The Possibility to demonstrate Non-Destructive Testing, i. e., X-ray micro CT, Ultrasonic testing for AM component like titanium, stainless steel with complex geometry is illustrated in Figure 5 and Figure 6 (Du Plessis, Le Roux, Els, Booysen, & Blaine, 2015)(Song et al., 2018). This study assures that defect-free parts can be produced from additive manufacturing with improved properties. Applying this NDE approach leads to optimizing the manufacturing process and examining the background that can occur through a computed comparative analysis (Hirsch et al., 2017). For achieving dimensional accuracy on AM Product, it's necessary to estimate distortion and residual stresses precisely before conducting the experimentation process (Mukherjee, Zhang, & DebRoy, 2017)(Szost et al., 2016). Especially in Aerospace and Nuclear Power plant, compositionally graded joints processed through AM are possibly preferred to reduce rapid distortion changes and residual stresses induced in different alloy joints (Mukherjee, Zuback, Zhang, & DebRoy, 2018). By using additive manufacturing, the Air-water heat exchanger for dry cooling of power plants is fabricated as a single part (Arie, Shooshtari, & Ohadi, 2017) and Printed Heat Exchanger (Hathaway, Garde, Mantell, & Davidson, 2018) as shown in Figure 7 a) and Figure 7 b) respectively.

It is possible to develop new electronic sensors through AM allowing for checking the desired parameters with a consistent resolution(Sarah K. Everton, Matthias Hirsch, Petros Stravroulakis, Richard K. Leach, 2016). There is an opportunity to explore AM technology to produce porous ceramics for tissue engineering(Ngo et al., 2018) with improved porous structure formation(Hwa, Rajoo, Noor, Ahmad, & Uday, 2017). The capability of product remanufacturing by adopting Additive Manufacturing methodology facilitating for reconditioning of worn out parts, which results in cost

saving by 20% to 80% compared to another Conventional method (Chen, Wang, Ou, He, & Tang, 2014).

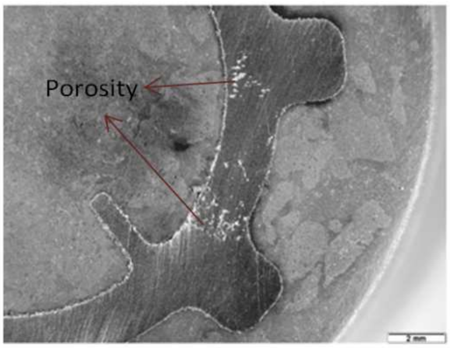


Figure 5: X-Ray Micro CT Scan Reveals the Presence of Porosity in the AM Component (Du Plessis et al., 2015)

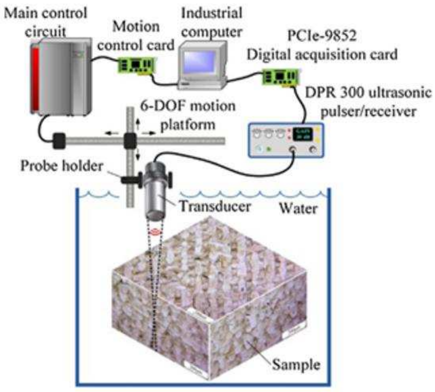
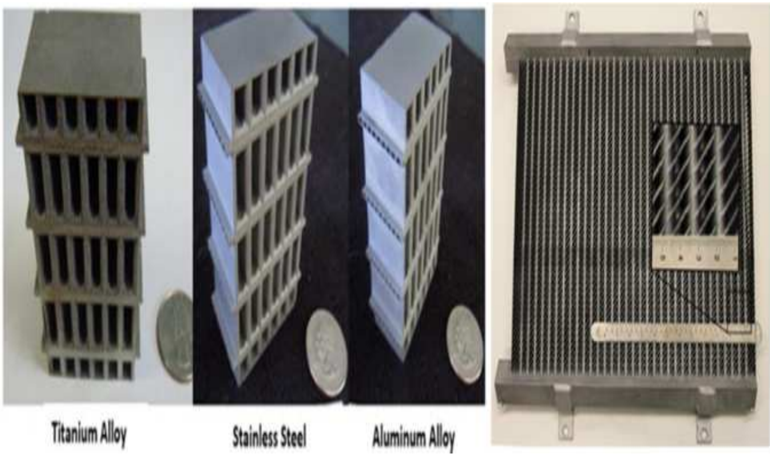


Figure 6: Schematic Diagram of Ultrasonic Setup (Song et al., 2018)

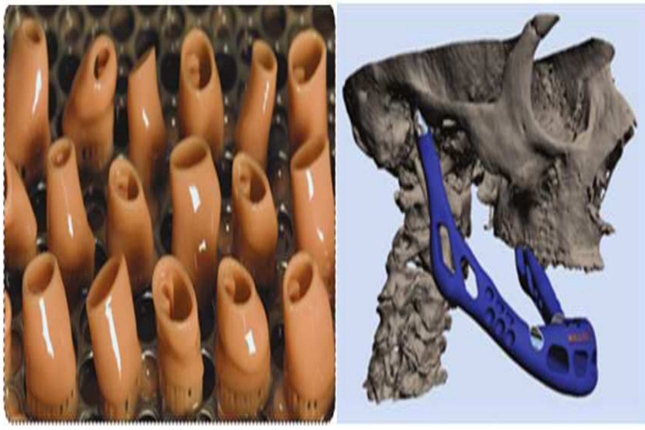


(a) (b)

Figure 7: (a) Fabricated Heat Exchanger Prototypes (Arie et al., 2017) (b) Printed Heat Exchanger (Hathaway et al., 2018)

In Biomedical Engineering, Manufacture of Hearing aids through 3D printing facilitates for altering the ear canal shape which differs from person to person. Also for producing the customized devices with better efficiency and lower price with a reduction in production lead time (Eyers & Potter, 2017) as shown in Fig.8 a). Especially in orthopedics, Components belonging to Medical Implants like Jaw Replacement are the most obvious application of this AM technology, Figure 8 b) (Banks, 2013).

Using Biomaterial porous magnesium for regeneration of bone tissue which exhibits biodegradation behavior, and its entirely interconnected porous structure results in Additive Manufacturing (Y. Li et al., 2017). Processing bio-ceramics through a unique SLA based Additive Manufacturing approach having biocompatibility and aesthetic value proved that it is an alternative approach for metals especially in implants (Varghese et al., 2017).



(a) (b)

Figure 8: (a) Hearing Aids Manufactured by Additive Manufacturing (Eyers & Potter, 2017), (b) Jaw Implants (Banks, 2013)

Additive Manufacturing Techniques associated in Concrete 3D Printing Building Systems and ability to produce multifunctional complex geometry structural elements without temporary supports as shown in Figure 9 a) and b), Multifunctionality is combined approach of enhancing the structural properties as well as the acoustic performance of component (Duballet, Baverel, & Dirrenberger, 2017). AM technologies facilitate for creating the ability for constructing buildings or structures which utilize on-site materials and eradiate the difficulty to find construction materials in that area (Camacho et al., 2018).

(a) (b)

Figure 9: (a) 3D Printed Space Truss (b) Acoustic Damping Wall (Duballet et al., 2017)

AM also helps in safeguarding the environment during manufacturing and transportation by significantly reducing pollutant effect in form of carbon footprint (Jiang, Kleer, & Piller, 2017).

CHALLENGES IN DEVELOPMENT OF ADDITIVE MANUFACTURING

The Latest Challenges in AM are listed below;

- Modules available for failure modes monitoring like Melt Pool, Porosity, Build Height, Depth Measurement is limited and to be addressed (Sarah K. Everton, Matthias Hirsch, Petros Stravroulakis, Richard K. Leach, 2016).
- Pre-processing tasks on Additive Manufacturing impacts the surface quality and accuracy of the part due to void formation and tessellation effect respectively. The quantity of material wasted depends on part orientation (Oropallo & Piegl, 2016).
- Controlling the Flowability and wettability of powder in SLS, SLM, and DED is a crucial task in the manufacturing of AM products (Hwa et al., 2017).
- The planning and scheduling for components to be processed on AM equipment play a vital role in decreasing the operational costs, providing service to customers with optimal amount thereby increasing the profitability of companies (Q. Li, Kucukkoc, & Zhang, 2017).
- Governing of mechanical properties like the flexural and compressive strength of 3D printed part by its printing directions and attaining anisotropy nature with heterogeneity is the limitation in AM products and research works are being conducted to address the issue (Paul, Tay, Panda, & Tan, 2018)(Kok et al., 2017).
- AM techniques in Construction field requiring the Interdisciplinary approach for attaining its full potential. This field still in its implementation stage without benchmark standards (Camacho et al., 2018).
- Establishing Manufacturing Strategy is highly necessary to achieve the quality of the part printed with economic benefit with consideration of all factors represented in Figure 10 (Reiher, Lindemann, Jahnke, Deppe, & Koch, 2017).
- Surface texture metrology is suggested in AM to inspect the features of the surface and interrelate the physical phenomena and process variable for addressing the specification compliant on products (Townsend, Senin, Blunt, Leach, & Taylor, 2016).
- The sustainability issues in additive manufacturing are to be addressed to reduce energy consumption, generation of waste and the printed part impact on the environmental effects during service (Burkhart & Aurich, 2015) (Kellens, Mertens, Paraskevas, Dewulf, & Duflou, 2017). For enhancing the sustainability, better thermal management and high-efficiency devices are to be adopted (Sreenivasan, Goel, & Bourell, 2010), and Sustainable materials are also playing a constructive role for the developing and reducing the cost and addressing the impact on the environment (Xin Wanga, Man Jiangb, Zuowan Zhoub, Jihua Goua*, 2017).

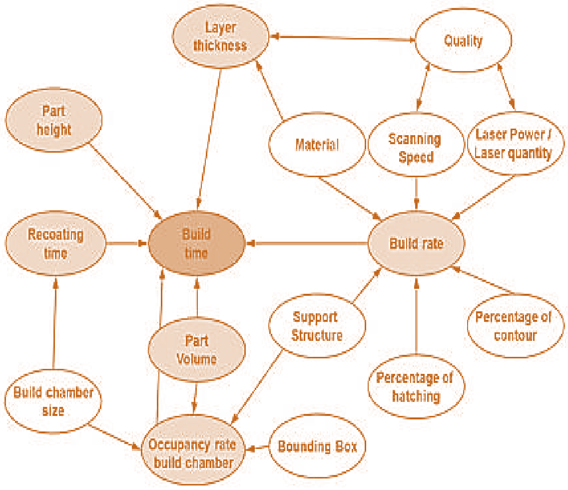


Figure 10: Factors Influencing Manufacturing Strategy (Reiher et al., 2017)

CONCLUSIONS

From the above literature, it is observed that 3D printing is now being transformed from the prototyping aspect for net shape manufacturing method with controllable performance in a rapid manner relative to some conventional techniques. For parts with high complexity and mass customization with fast delivery time to help in attaining a market requirement, Additive Manufacturing is well-suited processing approach. Though there is the rapid growth of AM, standardization procedure will need to implement in all stages of AM includes Design, Material and Process selection, Process Control like Machine Calibration, Preventive Maintenance, Machine Health Monitoring and Machine Qualification, Post Processing treatments like Heat Treatment, Hot Isostatic Pressing (HIP) and Surface Finish, Finished material properties through mechanical testing, microstructure analysis and Coupon testing and finally Non Destructive Evaluation and its validation. From the above AM techniques, it is noted that the specific constraints like Production time; Product Size; Setup Cost; Statutory Regulations is essential, and they are persisting during the initial stage of implementation of the technology in respective fields. Irrespective of the constraints and challenges, there is a scope for commercializing AM products in the global market which in turn leads to the production savings of less than 50% and an increased production speed of more than 400 % when compared to conventional methods by optimizing the constraints mentioned above. Integration of Additive manufacturing, Equivalent Manufacturing, and Subtractive Manufacturing into a single piece of equipment, i. e., Hybrid System, might result in valuable economic benefits. Finally, Uniform Standard Practices in AM Product Manufacturing with extensive research and support are the vital requirements to establish AM techniques in the global industrial scenario for yielding significant interest in the society near future.

COMPLIANCE WITH ETHICS GUIDELINES

Raj Mohan R, R. Venkatraman, S. Raghuraman declare that we have no conflict of interest or financial conflicts to disclose.

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